Osteoarthritis and Cartilage 19 (2011) 281–286

Osteoarthritis and Cartilage

OARSI OSTEOARTHRITIS RESEARCH SOCIETY INTERNATIONAL

Evaluation of unipodal stance in knee osteoarthritis patients using knee accelerations and center of pressure

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A R T I C L E I N F O

Article history:
Received 19 April 2010
Accepted 14 December 2010

Keywords:
Knee osteoarthritis (OA)
Unipodal stance
Knee accelerations
Center of pressure (COP)

S U M M A R Y

Objective: This study aims to compare knee joint instability and postural impairments during the performance of a unipodal stance task between patients having knee osteoarthritis (OA) and healthy elderly subjects using knee accelerations and center of pressure (COP) measurements.

Materials and methods: Twenty patients with medial knee OA and nine healthy individuals participated in this study. Three-dimensional (3D) knee joint accelerations and COP were measured during unipodal stance. The range and the root mean square (RMS) were extracted from medial lateral (ML) and anterior–posterior (AP) knee accelerations, whereas sway area, velocity, and ML and AP ranges were measured from the COP. The average parameters of three trials for each subject were compared between groups.

Results: Results show that knee OA patients exhibited a significantly higher range of knee acceleration in both ML (0.22 ± 0.08 g vs 0.15 ± 0.05 g) and AP (0.17 ± 0.06 g vs 0.06 ± 0.01 g) directions and a lower COP velocity (136.6 ± 22.3 mm/s vs 157.6 ± 18.4 mm/s) than did the healthy age-matched group. Significant correlations between the COP and knee acceleration parameters were also obtained.

Conclusions: This study confirmed that patients with knee OA displayed greater body sway than did able-bodied subjects. Moreover, using an accelerometric-based method, this study highlighted the higher knee joint instability in the frontal and sagittal planes in knee OA patients compared with able-bodied subjects during a unipodal standing task.

Introduction

It is well recognised that knee OA increases with the age and contributes to the decrease of functional capacity during daily life[1]. The preservation of functional capacity is also associated with the ability to maintain postural stability under both static and dynamic activities[1]. As individuals with knee OA display muscle weakness, loss of proprioception, obesity, and knee joint laxity[2], their postural stability may be affected. However, it is currently unknown how postural impairments are related to knee OA.

Postural impairments in the elderly population are well documented (see the review of Sturnieks *et al.*[3]), but no clear relationship has actually been established between the clinical factors associated with knee OA disease (e.g., knee laxity, muscle weakness) and the increase in postural instability. In fact, only a few studies have investigated postural impairments in the knee OA population[4–10]. Previous studies reported a higher sway index in knee OA patients compared with age-matched volunteers[9], a significantly higher center of pressure (COP) area in patients with painful knee OA compared with their able-bodied counterparts[8–10], a positive correlation between the increase in postural sway and radiographic findings (i.e., OA disease severity)[8,10]. Only the study of Hurley *et al.*[7] reported no difference in body sway, as measured by the displacement of the center of gravity (CoG), between knee OA patients and healthy volunteers.

The stability of the knee has been previously defined as the capacity of the joint to keep a position and to control movement under external loads[11]. The instability of the knee has also been related to phenomena like buckling, shifting or giving away of the joint[12]. The assessment of knee joint instability using accelerometric-based methods has recently been proposed and reported during gait in knee OA[12–14]. Previous work has also demonstrated that knee acceleration measurements are reliable and responsive to change in knee OA subjects[15,16]. However, to the best of our knowledge, no study has investigated simultaneously knee joint instabilities and postural impairments in knee OA patients during

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1063-4584/$ – see front matter
doi:10.1016/j.joca.2010.12.007

Table I
Participants' characteristics

	OA patients ($n = 20$)		Control group ($n = 9$)	
	Mean	SD	Mean	SD
Age (years)	63.7	7.1	66.0	7.1
Height (m)	1.6	0.1	1.6	0.1
Weight (kg)	81.1	19.2	66.3	14.9
BMI (kg/m^2)	31.4*	4.8	24.4	3.9

* Significant difference between groups with a $P < 0.05$

a standing task. Taking into account that individuals with knee OA present joint instability related to factors previously mentioned (i.e., muscle weakness and knee laxity)[17], we can suppose that knee instability might be associated with the increase in postural impairments.

Therefore, this study aims to examine knee joint instabilities and postural impairments in individuals having symptomatic knee OA during a single-limb stance using knee acceleration and postural sway measurements. We hypothesised that patients having knee OA will present larger knee accelerations and larger displacements of the COP in frontal and sagittal planes compared with able-bodied subjects. We also hypothesised that significant correlations between both measures should be found.

Methods

Subjects

Twenty patients with knee OA were included in this study. Patients were recruited from the Hospital Research Centre (CRCHUM) of the Notre Dame Hospital (Montreal, Quebec, Canada). All patients had predominant medial knee OA diagnosed by a physician, confirmed radiographically with the criteria developed by Altman *et al.*[18], and graded with the Kellgren–Lawrence (KL) scale (1–4)[19,20]. Patients were excluded if they were unable to stand unilaterally for 4 s and had vestibular, neurological or musculoskeletal disorders, fracture of the lower extremity, rheumatoid arthritis, and generalized OA. The mean age, weight, height and body mass index (BMI) and their corresponding standard deviations (SD) were 63.7 (7.1) years, 81.1 (19.2) kg, 1.60 (0.11) m and 31.4 (4.8) kg/m^2 respectively. Of the 20 patients, nine had slight OA disease (i.e., KL 1 or 2), whereas 11 had moderate to severe OA disease (i.e., KL 3 or 4).

Nine asymptomatic subjects were also included to form a control group. These asymptomatic subjects were evaluated by a physician and were excluded if they had joint pain, orthopaedic (joint fracture, joint laxity, OA, arthritis), or neurological problems. The mean and SD of age, weight, height and BMI were 66 (7.3) years, 66.3 (14.9) kg, 1.64 (0.1) m and 24.4 (3.9) kg/m^2, respectively.

No significant difference was found between group characteristics for age ($P = 0.43$), height ($P = 0.35$) and weight ($P = 0.05$), whereas a significant difference was present for BMI ($P = 0.001$) (Table I).

Both patients and asymptomatic subjects gave their written consent to participate in this study, which was previously approved by institutional ethics committees.

Task and instrumentation

Each subject performed a single-limb stance. Knee OA patients were asked to stand unilaterally on the most affected limb for a steady-state period of 4 s, whereas able-bodied subjects were asked to stand in a randomised order (i.e., right or left side). Six trials were performed and three were kept for further analysis.

The COP, three-dimensional (3D) knee kinematics, 3D linear relative accelerations, and angular velocities of the knee were collected in a synchronised way. COP was collected using two Kistler force platforms integrated into an instrumented treadmill (Adal 3D, Medical Development, France) and was expressed in the ankle coordinate system.

Linear accelerations and angular velocities were collected at femoral and tibial levels using two triaxial accelerometers (ADXL320, ±5 g) and two triaxial gyroscopes (Murata, ENC-03 J, ±400°/s), respectively (Physilog®, BioAGM, CH). To estimate linear accelerations at the knee joint coordinate system, two rigid bodies were designed. Each rigid body was mounted with four reflective markers, one accelerometer, and one gyroscope, and then was fixed on an exoskeleton (Fig. 1)[13]. The measurement of inertial systems (i.e., accelerometer and gyroscope) was expressed in the femoral and tibial body reference frames (i.e., removing the gravitational component from the accelerometer sensing axes and the alignment

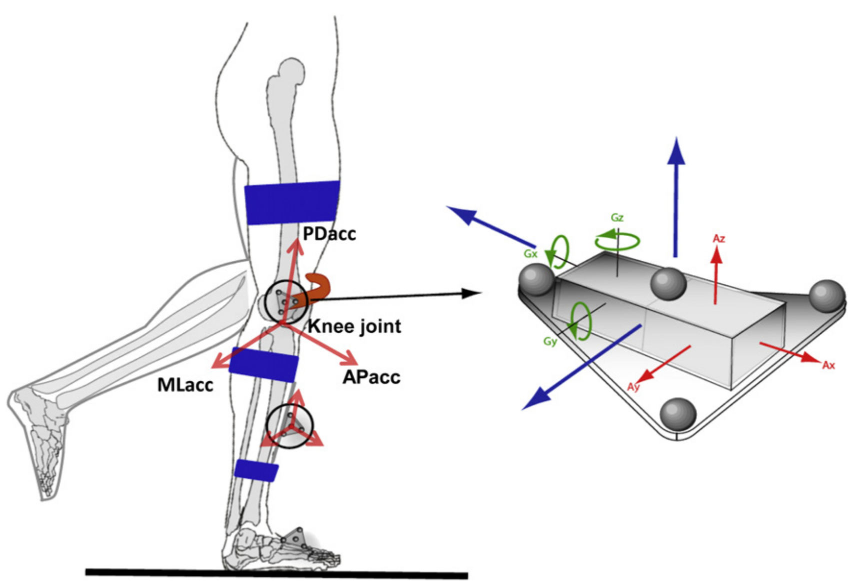

Fig. 1. Illustration of the instrumentation used during the unipodal task and related knee acceleration parameters.

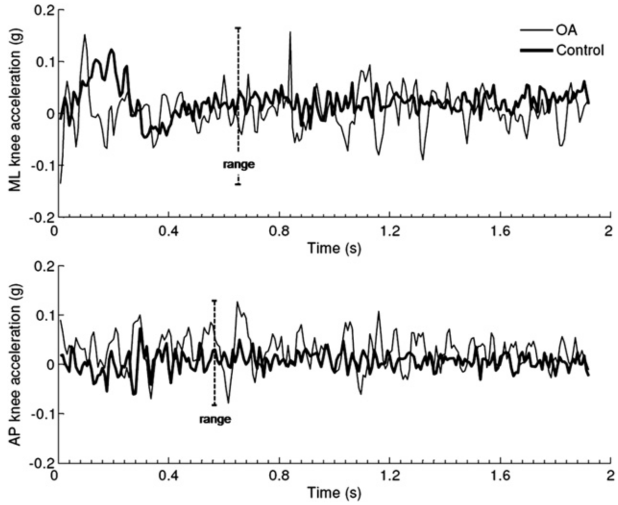

Fig. 2. Typical representations of knee acceleration signals for a knee OA patient and a control subject.

of the accelerometer axis with the femoral and tibial body reference frames). This method has been described and validated in previous studies[13,21]. Additional reflective markers were fixed onto both maleoli and sacrum to enable the determination of the knee joint coordinate system. The knee joint coordinate system was determined using the functional approach proposed by Hagemeister *et al.*[21]. Tibial and femoral accelerations were used to estimate 3D knee joint linear accelerations. To do so, femoral accelerations were expressed in the tibial body reference frame. Positive knee accelerations were set toward the medial, anterior, and distal directions, whereas negative accelerations were aimed at the lateral, posterior, and proximal directions, respectively. Figure 1 illustrates the instrumentation used (i.e., reflective markers, accelerometers, gyroscopes) and related accelerometric parameters. Lower-body kinematics data were simultaneously collected using a six-camera optoelectronic system (VICON 460, Oxford Metrics). Data were collected at a frequency of 120 Hz. An external trigger device was used to collect all data synchronously. The 3D position of the markers was filtered using the automatic singular spectrum analysis (SSA) with a window length of 10 samples[13]. The ground reaction forces were filtered using a fourth-order zero-lag Butterworth filter with a cut-off frequency of 30 Hz.

Data processing

The range and root mean square (RMS) values were calculated from the medial lateral (ML) and anterior–posterior (AP) knee acceleration signals (Fig. 2). The mean velocity, the sway area (i.e., the surface delineated by the convex-hull of the outlined contour of the COP), and the ML and AP ranges were calculated from the COP (Fig. 3). The mean knee flexion/extension and varus/valgus angles were also calculated. The average values of each parameter from the three trials were used for statistical analysis.

Statistical analysis

Two-tailed unpaired Student's *t*-tests were performed to compare the groups' characteristics in terms of age, height, and weight. To compare knee acceleration parameters, COP parameters, and knee angles (i.e., flexion/extension and varus/valgus) between knee OA patients and able-bodied subjects, one-way ANOVA or Mann–Whitney *U* tests for non-parametric measures were used. As the BMI was founded to be statistically significant between groups, the analysis was also done using the BMI as covariate. A significant P value was set at $P < 0.05$. The correlation between COP and knee acceleration parameters was also determined in the knee OA group using Spearman correlations.

Results

A comparison between the groups showed statistical significant differences in knee accelerations, COP parameters, and knee angles

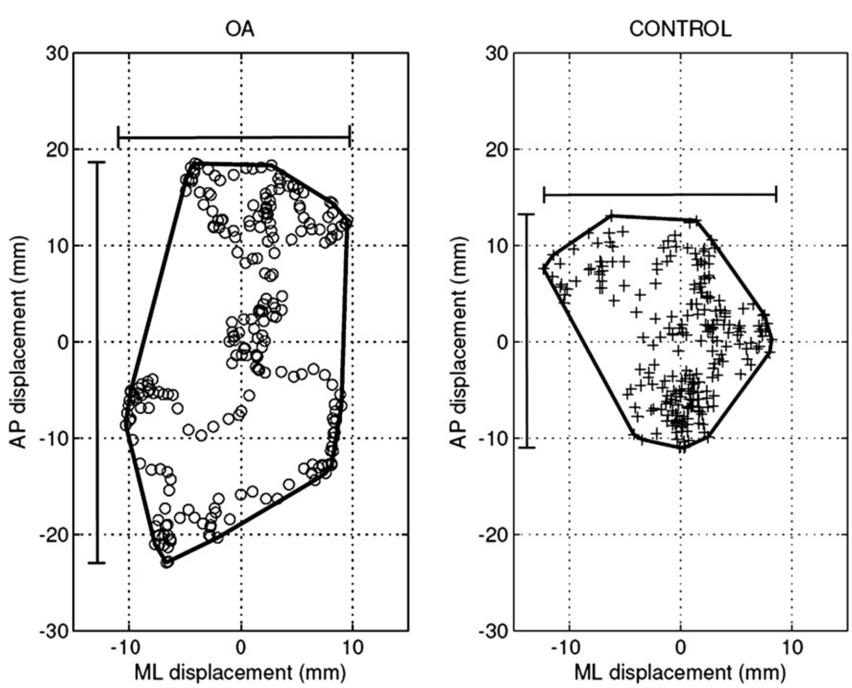

Fig. 3. Typical representations of parameters obtained from the COP for a knee OA patient and a control subject.

Table II
Mean and 95% of the confidence interval (CI) of all parameters obtained for OA and control groups

	OA patients ($n = 20$)			Control group ($n = 9$)		
	95% CI			95% CI		
	Mean	Low	High	Mean	Low	High
Acc ML range (g)	0.22*	0.06	0.12	0.15	0.04	0.11
Acc ML RMS (g)	0.03	0.01	0.01	0.03	0.01	0.02
Acc AP range (g)	0.17†	0.05	0.09	0.06	0.01	0.03
Acc AP RMS (g)	0.03†	0.01	0.01	0.01	0.00	0.00
COP Area (mm2)	397.14	153.98	295.73	311.75	106.16	301.10
COP ML (mm)	20.94	4.88	9.36	17.79	2.44	6.92
COP AP (mm)	27.97	5.15	9.90	27.23	4.96	14.08
COP velocity (mm/s)	136.61*	17.09	32.82	157.60	12.43	35.27
Mean knee adb/add (°)	5.20*	4.06	7.80	1.20	2.31	6.54
Mean knee flexion (°)	8.50	5.24	10.07	7.80	2.81	7.96

* Significant difference between groups with a $P < 0.01$.
† Still a significant difference between groups with a $P < 0.01$ using BMI as covariate.

(Table II). A significantly lower COP velocity ($P = 0.02$) was found in knee OA patients (136.6 ± 22.3 mm/s vs 157.6 ± 18.4 mm/s for the control group). In addition, a significantly higher ML range in knee acceleration, 0.22 ± 0.08 g vs 0.15 ± 0.05 g ($P = 0.02$), was noted. The AP range was significantly higher for the OA group (0.17 ± 0.06 g) when compared with the control group (0.06 ± 0.01 g, $P < 0.001$). A significantly higher AP RMS of 0.03 ± 0.01 g was found in the OA group compared with the control group (0.01 ± 0.00 g, $P < 0.001$). A significantly higher varus/valgus mean angle was also found in knee OA patients (5.2 ± 5.3° vs 1.2 ± 3.4°) ($P = 0.048$). Finally, no difference in mean knee flexion angle was found between groups (8.5 ± 6.9° in knee OA patients vs 7.8 ± 4.2° in the control group). Considering BMI as covariate, range and RMS of the AP knee accelerations were still significantly higher in knee OA group (Table II).

Significant correlations were obtained between COP and knee acceleration parameters (Table III). The highest correlations were found between the COP area and the range in AP knee acceleration ($r = 0.60$). The latter means that as the COP area increases, a greater acceleration range in the AP direction is detected at the knee joint.

Typical representations of knee acceleration signals for a knee OA patient and a control subject are shown in Fig. 2, and those of the sway area for the same subjects are presented in Fig. 3.

Discussion

In this study, knee OA patients showed greater knee instability and postural sway during a single-limb stance compared with the control group. Compared with control group values, knee OA patients displayed larger ranges of knee acceleration in ML of 32% and in AP of 65%, respectively. The RMS value of the AP knee acceleration was also larger: 67% in knee OA patients compared with the control group. These results suggest a larger instability at the knee joint level in both frontal and sagittal planes. These results are also in agreement with the findings of previous gait studies which compared sagittal and frontal planes knee accelerations in deficient knee patients (i.e., OA and ligament-insufficient knee) and control group[12,13].

A significant decrease in COP velocity in knee OA patients was also found during the single-limb stance. When combined with the high values of knee accelerations, this result suggests that OA patients have a higher instability at the knee level than at the ankle. Although no significant difference in the COP area was found between groups, knee OA patients tend to have higher values than do able-bodied subjects.

In knee OA, local mechanical factors have been linked with the development and the progression of the disease[1,22–25]. More specific factors, notably hip-knee-ankle misalignment, joint laxity, quadriceps weakness, and degradation of joint structure, have also been linked with joint instability. Many studies have already investigated the presence of knee instability in knee OA patients using knee laxity as the main outcome[17,26–28]. The results of this main outcome show an increase in frontal laxity (i.e., ML laxity) in OA patients when compared with normal subjects[17,26–28]. It should be noted, however, that the above studies[24–27] assessed knee joint instability under a non-weight-bearing condition and did not consider the influence of femorotibial loading, misalignment, proprioception, and muscle weakness, which are all important factors involved in postural stability. The study of Markolf *et al.*[29] demonstrated that the load on the knee had an important stabilization function by restraining movement between joint structures. Therefore, joint instability, as estimated by knee laxity outcomes, does not represent the same joint instability under dynamic and loading tasks.

Apart from a few studies that investigated joint instability in knee OA during gait[11–13], no previous study has attempted to assess knee instability under weight-bearing conditions. Both Turcot *et al.*[13] and Yoshimura *et al.*[12] used an accelerometric-based method and reported higher acceleration values in knee OA patients when compared with a normal population during gait. In a recent study, van der Esch *et al.*[11] failed to find a relationship between varus–valgus motion and knee joint instability during gait in patients with knee OA. Since the varus–valgus motion was not related to clinical measurements of joint instability (e.g., muscle strength, joint laxity, joint proprioception), the authors concluded that knee joint instability could not be measured by a varus–valgus motion[11]. In the present study, the varus–valgus motion was measured during a unipodal stance. We found that knee OA patients, compared with the control group, had on average a significantly higher varus–valgus motion (Table II). The discrepancy between our study and that of van der Esch *et al.*[11] may be attributed to methodological aspects such as the determination of joint coordinate systems and the tasks evaluated. Therefore, further studies are needed to confirm these results.

As far as we know, only one study has compared results obtained from force plate and accelerometer measurements obtained during a single-limb stance[30]. The authors concluded that, although a moderate correlation exists between acceleration values and COP parameters, different aspects of balance were investigated[30]. This is in agreement with the findings of the present study.

This study is also the first to propose an assessment of both knee joint instability and postural sway in OA patients. It was conducted to evaluate if an increase in knee instability could be directly linked to an increase in body sway. Our results show significant correlations between COP parameters and AP relative knee accelerations. As hypothesised, these results suggest that knee joint instability, measured with knee accelerations, influences postural stability in knee OA patients during a single-limb stance. In a recent study, Hunt *et al.*[10] aimed to identify factors related to single leg standing balance in medial knee OA patients. The authors reported that

Table III
Correlations (r) between knee accelerations and COP parameters

	COP area	ML COP	AP COP	COP velocity
	r	r	r	r
ML range	0.37	0.24	0.38	−0.19
ML RMS	0.37	0.29	0.38	−0.04
AP range	0.60*	0.47*	0.59*	−0.08
AP RMS	0.59*	0.46*	0.64*	−0.13

* Significant correlation with a $P < 0.05$.

standing balance was in part related to modifiable factors noting lower limb alignment, knee pain and quadriceps strength[10]. The fact that muscle (either by its atrophy or by its twitch activity) may be responsible for the dynamic stability of the knee during unipodal stance should have an important issue during unipodal stance support. In OA population, it is well recognised that muscular and specifically quadriceps weakness are present[1]. In another study, Greve *et al.*[31] evaluated the correlation between BMI and postural balance in unipodal support in healthy young population. The authors[31] found that high BMI subjects demand more COP displacements to maintain postural balance. This is in agreement with our data (Fig. 2, Table II). However, in the study of Greve *et al.*[31] the COP velocity was not assessed. Recently Alfieri *et al.*[32] investigated the influence of a regular physical therapy program on the COP trajectory and muscle adjustments necessary to maintain balance on orthostatic position. They found[32] that COP trajectory during unipodal position with open eyes decreased significantly after physical therapy intervention. They concluded[32] that the physical therapy intervention promoted decrease of body oscillation, recruitment, improvement and adjustment of the gastrocnemius and anterior tibial muscles, contributing to the postural balance improvement in unipodal position on senior population. In the present study we did not assess electromyography (EMG) activity of quadriceps, gastrocnemius and tibialis muscles. Further study on OA unipodal tests should involve EMG as well as COP measurements.

One limitation of this study is that each patient who was unable to complete the unipodal task for a period of at least 4 s was excluded from the study. Therefore, the results may have underestimated the knee instability of OA patients under this weight-bearing condition. Another limitation of this research is the small number of subjects in both groups. In this regards, we calculate the statistical power for all significant parameters detected in this study and found an average power of 90% using an alpha error level of 5%, showing that the number of subjects was enough to detect a difference when one exists. Another limitation is that the position during the unipodal stance has not been controlled between subjects. This was done for the reason that it would reflect more the daily life conditions. Finally, only knee accelerations and COP measurements were considered in the present study, even though other factors, such as muscle weakness, play an important role in balance control deficits. In fact, we can presume that quadriceps weakness, which is well recognised in knee OA patients, is closely linked with the larger AP knee accelerations obtained in knee OA compared with control subjects. However, this was beyond the scope of this paper. The aim was to determine if there was a relation between knee joint accelerations, considered as an estimation of knee instabilities, and COP measurements. Therefore and as discussed earlier, further studies are still needed to better understand the relation between balance control deficits in knee OA patients and all related factors.

The results of this study highlighted the higher knee joint instabilities in the frontal and sagittal planes in knee OA patients compared with control group values during a unipodal standing task and measured using a novel accelerometric-based method. The results also suggest that knee joint instability, like muscle weakness, proprioception, misalignment, and pain, should also be addressed as an important factor to assess in balance control studies as well as under weight-bearing conditions.

Role of the funding source

This project was supported by the Canadian Institute of Health Research (CHIR) as well as by the Natural Science and Engineering Research Council of Canada.

Authors' contributions

All authors contributed to the conception and design of the original study and approved the final submitted manuscript. The article was first drafted by KT and critically reviewed by RA, NA and JDG. Funding was obtained by RA and JDG. KT takes responsibility for the integrity of the article as a whole.

Conflict of interest

No conflict of interest

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